A NEW APPROACH FOR VANISHING LINE ESTIMATION

Po-Lun Lai
Alper Yilmaz
Photogrammetric Computer Vision Laboratory
Ohio State University
Columbus, OH 43210
lai.138@osu.edu
yilmaz.15@osu.edu

ABSTRACT

In photogrammetry and computer vision, retrieving object space information from images remains a fundamental task and numerous efforts have been dedicated to this specific topic. It is revealed in recent research papers that vanishing points and vanishing lines provide clues about the structures of the object space. A variety of approaches have been proposed either for single-camera systems or for multi-camera systems; nevertheless, they generally require existence of several linear features for estimating the vanishing points and lines. Instead of finding vanishing lines from several parallel line pairs, this paper introduces a new approach to estimate the vanishing line via linear features that are orthogonal to a reference plane. The approach is based on single-view geometry and only two parallel lines are required to be identified in the image. These lines also generate the vanishing point in the orthogonal direction of the plane, and the focal length can be evaluated directly from the geometric relation between this point and the derived vanishing line. A calibration pattern and an image of a real world scene are tested in the experiments to verify the legitimacy and practicability of the proposed approach.

INTRODUCTION

With the advent of powerful personal computers and the increasing availability of digital imagery, retrieving three-dimensional (3D) information from two-dimensional (2D) images becomes more practical to general users. Among the various methods proposed for accomplishing the task, a new line of research, which utilizes projective geometry and homogeneous coordinates has emerged and thrived recently. Depending on the setting, the geometric relationship between the object space and the image space is described via either similarity, affine or projective transformations. It is known that these transformations can be recovered by analyzing the vanishing points and vanishing lines.

The most common approach to find the vanishing line for a scene plane is first to determine two vanishing points from two sets of linear features parallel to the plane, and then construct the vanishing line through the two vanishing points. However, these linear features may not be readily available for every scene and their generation may be prone to errors if the linear features are short in distance. Other methods include estimation from equally spaced coplanar parallel lines and using orthogonality relationship among vanishing points and lines (Hartley and Zisserman, 2003). However, these methods still require parallel lines on the scene plane or the specific configurations which are hard to retrieve for practical use.

In addition to the intuitive estimation from parallelism, other alternative approaches have been proposed for detecting the vanishing line. For instance, Havasi and Sziranyi (2006) utilize the motion statistics derived from a video sequence to address the problem of estimating the horizontal vanishing line. Schaffalitzky and Zisserman (2000) demonstrated that by grouping together the features with a specific geometric relationship, the vanishing points and vanishing lines are automatically detected and estimated. In their work, Minagawa et al. (1999) define a likelihood function including obvious vanishing point and vanishing line parameters based on a Gaussian mixture density model for the simultaneous detection of vanishing points and vanishing line.

The information about the object space implied by the vanishing lines can be extracted for a variety of applications, including but not limited to camera calibration and object detection. In 1991, Wang and Tsai employ a hexagon as the calibration target to generate a vanishing line of the ground plane from its projected image. The camera calibration parameters including the orientation, position, and focal length of a camera are then estimated analytically. In the paper of Shaw and Barnes (2006), a new detector is described for finding perspective rectangle structural features by recovering the edge points that are aligned along the vanishing lines. For object detection, Okada et al. (2003) present a method for detecting vehicles as obstacles in various road scenes using a single onboard camera. Vehicles are detected by the motion constraint of the ground plane, which is derived from the projective invariant combined with the vanishing line of the plane that is a prior knowledge of road scenes. Another application of navigating a 3D scene model constructed from the picture using a single vanishing line is proposed by Kang et al. (2001).

In spite of the claimed practicability of these proposed methods, most of them generally require complicated computation model or existence of abundant knowledge about the object space. In this paper, a simple yet geometrically constrained approach for the vanishing line estimation and its extension for the approximation of the camera focal length are presented. This approach requires only two parallel linear features and their relative lengths or heights as known ground truth and as a result, provides more flexibility for general cases.

VANISHING LINE ESTIMATION

Instead of using lines parallel to the reference scene plane, in this section we introduce a new method for retrieving the vanishing line from the vanishing point in the direction parallel to the plane normal. A brief introduction of the fundamental projective geometry is provided for the completeness of the proposed approach.

Projective Geometry

The relationships between an object and its image can be described with the projective geometry. When represented in the homogenous coordinates, in which the last component is set to one, the projection of a point $\mathbf{X_w} = [X\ Y\ Z\ 1]^T$ in the object space to a point $\mathbf{x} = [x\ y\ 1]^T$ in the image space is expressed in terms of a direct linear mapping:

$$\lambda \mathbf{x} = \mathrm{P}\mathbf{X_w} = [\mathbf{p_1} \quad \mathbf{p_2} \quad \mathbf{p_3} \quad \mathbf{p_4}] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{1}$$

where λ is the scale factor due to the projective equivalency $\mathbf{x} = \lambda\mathbf{x}$, P is a 3 × 4 camera projection matrix and $\mathbf{p_i}$ the i^{th} column vector from P. When the imaged points are lying on a plane in the object space, the projection matrix given in equation (1) reduces to plane projective transform. Without the loss of generality, if we choose the reference plane in the scene as the "ground plane" which is located at Z = 0, the linear mapping given in (1) reduces to the homography transform:

$$s\mathbf{x} = \mathrm{H}\mathbf{X'_W} = [\mathbf{p_1} \quad \mathbf{p_2} \quad \mathbf{p_4}] \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}. \tag{2}$$

This formulation introduces another scale factor *s* which is imposed to assure the last elements of the coordinates being one. The homography matrix H is a direct mapping from the points lying on a plane in the object space to the projected points on the image. Due to the fact that the third column of projection matrix P in (1) corresponds to the vanishing point for the Z direction, equation (1) can be rearranged by substituting $\mathbf{p}_3$ with $\mathbf{v_z}$ as

$$\lambda \mathbf{x} = [\mathbf{p_1} \quad \mathbf{p_2} \quad \mathbf{p_4}] \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} + Z\mathbf{v_z}. \tag{3}$$

Combining the above equation with (2) results in

$$\lambda \mathbf{x} = s\mathbf{x}' + Z\mathbf{v_z} \tag{4}$$

where λ is the sum of s and Z due to the fact that the last components of the homogeneous coordinates being one. The scale factor s is computed from the measurements of image point $\mathbf{x}$ and $\mathbf{x}'$ with presumed Z value. Once s is determined, the estimation of any image point along the line originating from $\mathbf{x}'$ to $\mathbf{v_z}$ is achieved by setting Z to different values.

Vanishing Point and Vanishing Line

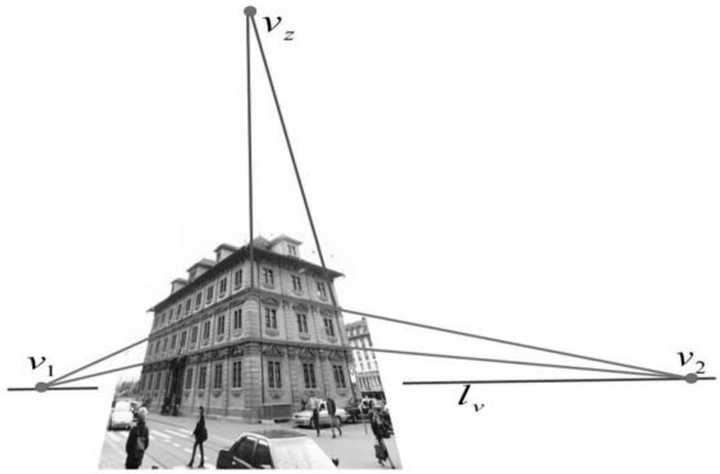

Figure 1. The typical formation of vanishing points and vanishing line. The cross product of two vanishing points on a plane provides the vanishing line $\mathbf{l_v}$. The vanishing point of the direction normal to the plane is denoted as $\mathbf{v_z}$.

A parallel line pair in the object space, when projected to the image plane, intersects at a single point referred to as the vanishing point (Figure 1). Assume that two points $\mathbf{x_1}$, $\mathbf{x_2}$ are observed along the image of one of the parallel lines, and $\mathbf{x_3}$, $\mathbf{x_4}$ are along the other, then the vanishing point $\mathbf{v}$ is computed from the cross products as $\mathbf{v} = (\mathbf{x_1} \times \mathbf{x_2})\times(\mathbf{x_3} \times \mathbf{x_4})$.

In Figure 1, the vanishing line $\mathbf{l_v}$ corresponds to the horizon and is intuitively determined by a pair of vanishing points as illustrated. A novel approach for the vanishing line estimation utilizing a single vanishing point and the scale ratio is proposed in this paper. This approach exploits the information implied in the geometric relations between the principle point **pp**, the vertical vanishing point $\mathbf{v_z}$ and the camera center **cc**, as depicted in Figure 2.

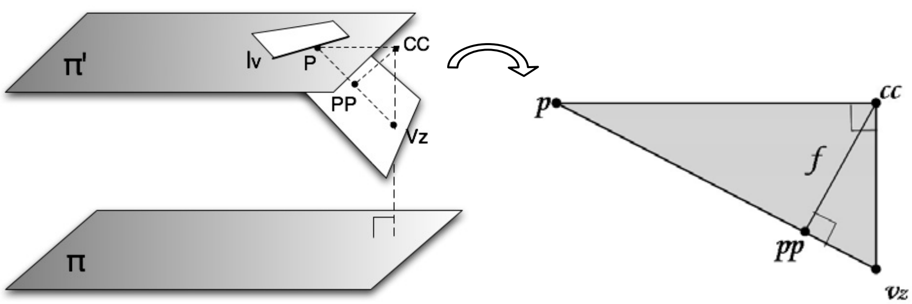

Figure 2. (a) The geometric representation between the vanishing point of a reference direction and the vanishing line of the planes orthogonal to the direction. (b) The similar right triangles formed by the four points in (a).

The projective geometry shown in Figure 2 reveals that the vertical vanishing point $\mathbf{v_z}$ is the image of the vertical projection of the camera center on the ground plane π. The vanishing line $\mathbf{l_v}$ is the intersection of the image plane and the plane parallel to the ground plane and passing through the camera center. The line passing through the principle point and the vanishing point is obtained by $\mathbf{l_{pp}} = \mathbf{pp} \times \mathbf{v_z}$. Let this line intersect the vanishing line at point **p** and it is observed that $\mathbf{l_{pp}}$ is perpendicular to $\mathbf{l_v}$. In other words, if $\mathbf{l_{pp}}$ is represented in the homogeneous coordinates as $[a\ b\ c]^T$, then the set of lines perpendicular to $\mathbf{l_{pp}}$ is in the form of $[b\ {-a}\ d]^T$ where d is an unknown factor. In order to determine d for the specific vanishing line $\mathbf{l_v}$, we utilize the property of scale ratio introduced in our previous work (Lai and Yilmaz, 2008):

Lemma: Scale ratio of two image points. When projecting two points $\mathbf{X_1}$, $\mathbf{X_2}$ lying on a plane in the object space onto the corresponding points $\mathbf{x_1}$, $\mathbf{x_2}$ in the image space using homography, the ratio of the scale factors s_1 and s_2 is the inverse proportion of the distances from the image points to the vanishing line of these parallel planes.

In other words, if the scale factors in equation (2) for two points $\mathbf{x_1}$, $\mathbf{x_2}$ are pre-determined, and let $D(\mathbf{x_i}, \mathbf{l_v})$ denotes the distance from point $\mathbf{x_i}$ to the vanishing line $\mathbf{l_v}$, then

$$\frac{s_1}{s_2} = \frac{D(\mathbf{x_2}, \mathbf{l_v})}{D(\mathbf{x_1}, \mathbf{l_v})} = \frac{bx_2 - ay_2 + d}{bx_1 - ay_1 + d}. \tag{5}$$

In the equation, d is the only unknown and is given by

$$d = \frac{s_2(bx_2 - ay_2) - s_1(bx_1 - ay_1)}{s_1 - s_2}. \tag{6}$$

The determination of d fixes the vanishing line from the infinite number of lines of the same direction. The additional information provided by the vanishing line can be directly extended for the estimation of the camera focal length as is discussed in the following section.

Focal Length Estimation

The geometry formed by the points in Figure 2(a) is redrawn as Figure 2(b) for clearer demonstration. In the ideal case where the effects of lens distortions are negligible, the four points depicted in Figure 2(b) make up two triangles $\Delta(\mathbf{cc}, \mathbf{pp}, \mathbf{v_z})$ and $\Delta(\mathbf{p}, \mathbf{pp}, \mathbf{cc})$. The focal length f is the distance from the camera center to the image plane, which equals the distance between **cc** and **pp**. By similar triangles, we may write

$$f^2 = D(\mathbf{p}, \mathbf{pp})D(\mathbf{pp}, \mathbf{v_z}) \tag{7}$$

Assume the principle point lies at the image center, and the vanishing line $\mathbf{l_v}$ is estimated from the scale ratio, the point **p** is obtained from the cross product of $\mathbf{l_v}$ and $\mathbf{l_{pp}}$. Note that the computation for the focal length using equation (7) fails under the degenerate conditions in which either $\mathbf{v_z}$ or **p** falls at infinity, meaning the image plane is orthogonal or parallel to the reference plane.

EXPERIMENTS

An image downloaded from the website http://www.vision.caltech.edu/bouguetj/calib_doc/index.html is used to demonstrate the procedure. The image contains a calibration pattern providing abundant linear features and edge points to be identified. In the experiment, only four points are manually selected as shown in Figure 4. Assume the reference plane includes points $\mathbf{x_1}$ and $\mathbf{x_2}$ and is orthogonal to the calibration pattern in the object space. The distances between $\mathbf{x_1}, \mathbf{x_1}'$ and $\mathbf{x_2}, \mathbf{x_2}'$ are set to 80 and 100 respectively. Here we note that only the relative lengths, not the actual lengths in the object space, are required. These four points provide the vanishing point in the direction orthogonal to the reference plane. The vanishing line of the reference plane is then obtained from the scale ratio.

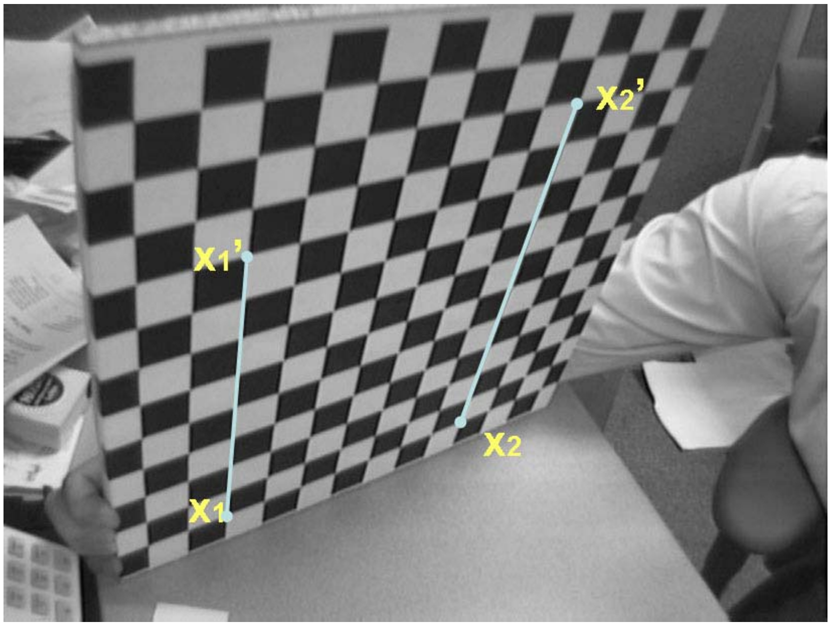

Figure 3. Experiment using the image of a calibration pattern.

The vanishing line $\mathbf{l_v}$ is estimated to be $[-0.0006404, 0.0022861, 1]^T$ in the experiment. More robust estimation can be achieved by using multiple features and their scale ratios. The four points in Figure 2(b) are computed explicitly and then the focal length f = 622.52 (pixels) is estimated by equation (7). Compared to the provided calibration results in which f is approximately 657 pixels after optimization (with uncertainties), the outcome from the proposed approach is quite satisfactory, considering only four measurements are involved.

Figure 4. Experiment on the image of a building.

Same procedure is applied to another image provided by ISPRS (http://www.isprs.org/data/zurich/default.aspx) shown in Figure 4. This experiment reveals the validity of applying the proposed approach on real world scenes. The estimated vanishing line is $\mathbf{l_v} = [0.00085766, 0.00029888, 1]^T$ and the computed focal length f = 1654.7 pixels. The given parameters come with the dataset state that the calibrated focal length derived by self-calibration is 1572.3 pixels and is close to the computed value. The discrepancy is mainly due to the offset of the principle point and the unavoidable lens distortion in the image. However, this approach still provides a fast way to obtain the approximated results which may be adopted as initial estimates for other algorithms.

CONCLUSION

In this paper we have presented a novel approach for the estimation of vanishing line from a single vanishing point. Dissimilar to other methods which detect the vanishing line passing the vanishing point, the approach estimates the vanishing line for the planes orthogonal to the direction instead. In this paper we also demonstrate the technique for finding the camera focal length geometrically by incorporating the information provided by the estimated vanishing line and vanishing point. More information about the 3D object space may be extracted from this combination for the applications such as camera calibration and object shape recovery in the future.

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